AFRL-OSR-VA-TR-2013-0521

CTAIR CONSTRUCTAL TREE STRUCTURES FOR MECHANICAL STRENGTH AND COOLING OF AIRCRAFT

ADRIAN BEJAN

DUKE UNIVERSITY

07/05/2013
Final Report

DISTRIBUTION A: Distribution approved for public release.

AIR FORCE RESEARCH LABORATORY
AF OFFICE OF SCIENTIFIC RESEARCH (AFOSR)/RSA
ARLINGTON, VIRGINIA 22203
AIR FORCE MATERIEL COMMAND

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE *(DD-MM-YYYY)*
06-28-2013

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
7/1/2010 - 6/30/2013

4. TITLE AND SUBTITLE
CTAIR CONSTRUCTAL TREE STRUCTURES FOR MECHANICAL STRENGTH AND COOLING OF AIRCRAFT

5a. CONTRACT NUMBER
FA9550-10-1-0347

5b. GRANT NUMBER
FA9550-10-1-0347

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Adrian Bejan

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Duke University
2200 W. Main St. Ste 710
Durham, NC 27705-4677

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF OFFICE OF SCIENTIFIC RESEARCH
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Districution A - Approved for Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project developed the fundamental features and strategy for the design of vascular solid structures with embedded volumetric functionalities: vascular flow access throughout the solid volume, superior overall mechanical strength, and volumetric self cooling. The research was based on constructal design, which is the philosophy that the flow and solid structures are free to morph hand in glove to provide greater access to all the currents including the flow of stresses. The project was constructed in several stages: the natural emergence of vascular design in the pursuit of greater flow access, the design of vascular structures for volumetric cooling and mechanical strength, the merits of hybrid designs consisting of grid & tree channels, vascularized plates subjected to randomly moving heat sources, and the overall design merits of allowing the flow architecture to morph more and more freely. The main feature of all this work is that it is fundamental. The design principles developed in this project have applicability across the spectrum of mechanical structures with embedded heating, cooling, and fluid flow.

15. SUBJECT TERMS
Constructal law, vascular design, flow of stresses, self cooling, self healing

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*

FINAL PERFORMANCE REPORT

This research was devoted to developing the conceptual strategy and design for vascular solid structures with several volumetric functionalities: vascular flow access throughout the solid volume, mechanical strength, self-cooling capability, and with vascular features that are essential for self-healing composites as well.

The research was based on constructal design, which is the philosophy that “design” is an evolutionary process with direction, in animate, inanimate and purposefully made objects. The direction is toward flow architectures that provide greater and greater access to what flows. Thermodynamically, this evolutionary design leads to greater efficiency, greater strength, lighter bodies, greater staying power, and designs that look more natural and unifying.

The work that this project produced is heavily documented in the best journals of applied physics and thermofluid science. Here I present an outline of the main achievements.

First, we showed that vascular design emerges naturally when a volume is bathed by a single stream in turbulent flow. The stream enters the volume, spreads itself to bathe the volume, and then reconstitutes itself as a single stream before it exits the volume. We showed that in the pursuit of a smaller global flow resistance and larger volumes, the flow architecture changes stepwise from a stack of identical elements bathed in parallel flow (like a deck of cards) to progressively more complex structures configured as trees matched canopy to canopy. The transition from one architecture to the next occurs at a precise volume size, which is identified. Each transition marks a decrease in the rate at which the global flow resistance increases with the volume size. This decrease accelerates as the volume size increases. The emergence of such vasculatures for turbulent flow is compared with the corresponding phenomenon when the flow is laminar. To predict this design generation phenomenon is essential to being able to scale up the designs of complex flow structures, from small scale models to life size models. The constructal law is a bridge between the principles of physics and biology.

Next, we explored the use of vascular design that provides cooling and mechanical strength at the same time. We illustrate the concept with a circular plate vascularized with embedded channels. The cooling fluid enters to the plate from the center or from the rim, and leaves after it cools the plate down to an allowable temperature level. The vascular cooling channels also affect the mechanical strength of the plate. We simulated numerically the thermofluid and mechanical behavior for three different structures; radial, dendrites with one pairing level and dendrites with two pairing levels. We found that for a given set of conditions (applied pressure difference, coolant inlet position, and number of the cooling channels) there is one configuration that is best; however, there is no single configuration that is best for all conditions.

The next architecture was a vascular structure that is a combination of one grid and several peripheral trees. The designs of trees with grid canopies provide greater robustness than purely dendritic designs. The coolant fluid enters the slab from the center or from the rim, cools the slab to an allowable temperature level, and then exits. Numerical simulations show the flow of the fluid, heat, and stresses. The results indicate that the lowest peak temperature and lowest flow resistance can be achieved with radial channels, and the lowest peak stress can be achieved with trees with canopies. The peak stresses are the lowest when the configuration is a hybrid grid and tree design. There is an optimal ratio of the grid length divided by the slab length for each specified fraction of the fluid volume occupied by the radial channels. When the heating is concentrated in a small area, the peak temperature is smaller when the heated spot is closer to the center of the slab.

We moved away from the steady heating and loading scenarios, and we considered a plate heated by a moving beam. We showed that the plate can be cooled effectively by fluid that flows through a vasculature of channels embedded in the plate. The vascular designs studied are radial, grid and hybrid (radial + grid). The peak temperature of the plate changes with the path and direction of the moving beam. The strength, size and speed of the beam vary. The peak temperature increases as the beam strength and size increase and as the speed of the beam decreases. The grid and hybrid designs are robust because of loops present in the flow structure. The pressure difference that drives the fluid flow varied. The channel diameter ratios that provide greatest flow access are reported. The cooling performance of the multiscale grid structures is less sensitive to the changes in beam path than the cooling performance of the other structures studied. The effect of adding a vascular structure to the design is dramatic.

Finally, we focused on the time-evolution of the vascular tree design. We proposed to discover the tree, and not assume it. We showed that spreading and collecting flows are united by a design feature known as the S-curve: when plotted versus time, the size of the domain that is filled or emptied has a history that is shaped as an S. We found that the fastest spreading or collecting (i.e. the steepest S curve) is discovered by allowing the tree architecture to morph freely, toward greater access over time, in accord with the constructal law of design in nature. The angles between the lines of the invading flow architecture can be selected such that the overall flow proceeds the fastest, covering the greatest territory at any moment. The design is a sequence of two distinct phenomena: “invasion” by channels and branches that grow fast and “consolidation” by slow diffusion perpendicular to the channels. Invasion and consolidation collaborate hand-in-glove to facilitate the spreading or collecting over the available finite area or volume.

The above highlights represent only a portion of what this research project has produced for the development of a constructal design strategy for vascular bodies with multiple volumetric functionalities. In addition, we formulated these findings to fit in the grater context of defense-sponsored research, and to communicate it to the wider public [refs]. This activity of greater and greater impact for this project will continue beyond 30 June 2013.